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ON THE RAPID VARIABILITY OF CENTRAL STARS OF PLANETARY NEBULAE

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ABSTRACT

Envelope models for central stars of planetary nebulae have been constructed with Carson's new radiative opacities. A stability analysis of these envelopes indicates that, for a sufficiently high luminosity, the fundamental mode of radial pulsation is excited by the κ-mechanism, operating in the CNO ionization zone. At somewhat higher luminosities the lowest overtones also become unstable. This may possibly explain the rapid variability that is observed in some central stars, if the time scale of the variations is minutes to hours.

Subject headings: nebulae: planetary — stars: early-type — stars: interiors — stars: pulsation

I. INTRODUCTION

Rapid light variability of low amplitude has been reported for a number of central stars of planetary nebulae. The time scale of the variations must be something less than weeks (Kohoutek 1966; Abell 1966) and is definitely known in some cases to be close to hours (Liller and Shao 1968; Abell 1976), minutes (Lawrence, Ostriker, and Hesser 1967), and possibly even seconds (Alekseev 1973). Other central stars, however, are either quiescent or at least nonperiodic on a time scale of seconds to a few minutes (Lasker and Hesser 1971). But it should be recognized that the effect of bolometric correction in masking visual light variations is important for such hot stars (Simon and Stothers 1970), and so variability must necessarily be difficult to detect.

In some theoretical models of central stars a helium-burning shell exists and becomes periodically thermally unstable, with a characteristic time scale of tens (Paczyński 1975) to thousands (Rose 1966, 1967) of years. But this is evidently too slow to account for the most rapid variations that are observed. However, around the epoch of the peak of the helium flash, the nuclear reactions sometimes destabilize the models in the fundamental radial mode of pulsation (Rose 1967) and possibly in the radial overtones as well (Sastri and Simon 1973). In spite of this, the time interval during which pulsational instability exists is very short compared to the duration of either the flash or the interflash period, and therefore this mechanism is unlikely (at least for most central stars) to account for the rapid variability that is observed. Moreover, not all of the suggested models for central stars have burning shells, and, in those models in which a *carbon* shell is ignited, the thermal flashes do not seem to lead to pulsational instability (Marshall and Van Horn 1973).

If the observed variability is, in fact, due to a pulsation of some sort, then perhaps the opacity (κ) mechanism is responsible. Unfortunately, the abundant elements hydrogen and helium become completely ionized just below the photosphere of such hot stars, and the excitation mechanism that produces Cepheids is unlikely to work here. But the ionization of the CNO elements at deeper layers may drive pulsations, as a direct consequence of the large opacity "bump" that has been discovered in recent recomputations of stellar opacities by Carson (1976). In deriving these opacities the "Thomas-Fermi" model of the atom has been substituted for the customary "hydrogenic" model, for elements heavier than hydrogen and helium; the new opacity bump occurs over a broad temperature range around 10^6 K and at very low densities. Since the effect of the bump is already known to be most marked in stellar envelopes with a high luminosity-to-mass ratio, the purpose of the present paper is to determine whether central stars of planetary nebulae may be thereby pulsationally destabilized.

II. THEORETICAL RESULTS

The basic input physics for calculating the equilibrium and pulsational properties of the present stellar models is the same as that adopted previously for other types of stellar models with a high L/M ratio (Stothers 1976). Here we remark that convection may occur in the CNO ionization zone and that the standard mixing-length theory of convection has been adopted to calculate the properties of the unstable layers, with the ratio of mixing length to pressure scale height taken to be $\alpha = 2$. The convective flux is assumed either (1) not to interact at all with the pulsations or (2) to adapt instantaneously to them. Linear nonadiabatic pulsation theory is applied to the models to compute the lowest (and a small sample of very high) normal modes of radial pulsation. Since the pulsation amplitudes drop off sharply below the stellar surface, only the outer part of the envelope of the star needs to be calculated and may be simply specified by the total stellar mass M, the envelope luminosity L (assumed to be constant with depth), the effective temperature T_e, and the envelope composition parameters X (hydrogen) and Z (metals), without any knowledge of the structure of the core.

Masses of 0.5 and 1 $M_\odot$ have been selected, along with a range of envelope compositions running from a normal hydrogen-rich mixture to a completely hydrogen-exhausted one. The evolutionary picture envisaged here is that of a star which has attained a late state of evolution, where it possesses a degenerate carbon or oxygen core of low mass. Most of the envelope has been expelled in the form of a planetary nebula, and the remnant appears as a highly luminous object of low surface gravity, which is contracting rapidly across the H-R diagram toward hot effective temperatures before fading into a white dwarf. The relevant luminosities range from $\log (L/L_\odot) = 0$ to $\log (L/L_\odot) = 5$, although the latter luminosity is somewhat above the Eddington limit. Pulsational instability has been searched for in the effective-temperature range $\log T_e = 4.4$–5.2 that is characteristic of these luminous, hot subdwarfs.

In all of the computed models the pulsation amplitudes drop to negligible values in layers still too cool to burn hydrogen or helium. Therefore, the envelope masses that are implied by our calculations lie significantly below the semiempirical upper limits given by Kovetz and Shaviv (1973).

All the models are pulsationally stable for luminosities approximately equal to $L/L_\odot = 10^3(M/M_\odot) \times (Z/0.04)^{-1.7}$ and fainter. At brighter luminosities, a broad instability strip abruptly appears whose blue edge is probably much hotter than $\log T_e = 5.0$ and whose red edge lies, in most cases, at $\log T_e \approx 4.6$. At the highest luminosities considered, the instability strip stretches to very low effective temperatures and probably merges with the Cepheid instability strip. Computational difficulties arising from the strongly nonadiabatic behavior of the envelope or, in other cases, from lack of knowledge of the structure of the core have prevented our consideration of any higher luminosity-to-mass ratios than $L/M = 10^4\, L_\odot/M_\odot$ or of effective temperatures higher than $\log T_e = 5.0$. However, pulsational instability undoubtedly extends to brighter luminosities and to hotter effective temperatures than this, unless convection quenches the pulsations at the brightest luminosities of all. It should be noted that our derived CNO-ionization instability strip for these luminous pre–white dwarfs is analogous in many ways to the helium-ionization (Cepheid) instability strip for ordinary white dwarfs (see Vauclair 1971).

Collected results for the fundamental mode of pulsation are given in Table 1, which lists the blue and red edges of the theoretical instability strip for each combination of mass, luminosity, chemical composition, etc. Also given are the pulsational period and Q-value for the red edge of the strip, where $Q = \text{Period}(M/M_\odot)^{1/2}(R/R_\odot)^{-3/2}$. This latter quantity does not vary to any great extent across the strip, but the period of the fundamental mode increases from several minutes to a day, from the blue edge to the red edge.

For the case of 1 $M_\odot$ with $(X, Z) = (0, 0.02)$ and with nonadaptive convection, we have also investigated the stability of the first and second overtones. Both overtones become unstable at a luminosity just below $\log (L/L_\odot) = 4.0$; the blue edge is definitely hotter than $\log T_e = 5.0$, and the red edge lies at $\log T_e \approx 4.70$ (for both overtones). Hence the overtones are somewhat less unstable than the fundamental mode. Instability of very high overtones would be required to produce pulsation periods of seconds, but a cursory search of the models for 1 $M_\odot$ reveals no instability at periods this short.

TABLE 1

Blue and Red Edges of the Pulsational Instability Strip for Hot Subdwarfs with Low Masses (fundamental radial mode only)

$M/M_\odot$	X	Z	Convection $\alpha = 2$	$\log (L/L_\odot)$	$\log T_e$ blue	$\log T_e$ red	P (hr) red	Q (day) red
0.5	0.00	0.02	Nonadaptive	3.25	4.88	4.64	0.9	0.041
				3.50	(> 5.0)	4.59	2.7	0.057
				3.75	(> 5.0)	(< 4.4)	(?)	(?)
1.0	0.73	0.02	Nonadaptive	3.25	Stable	Stable	...	...
				3.50	4.91	4.72	0.6	0.041
				3.75	(> 5.0)	4.62	2.4	0.058
				4.00	(> 5.0)	(< 4.4)	(?)	(?)
1.0	0.00	0.02	Nonadaptive	3.25	Stable	Stable	...	...
				3.50	4.77	4.65	0.8	0.034
				3.75	(> 5.0)	4.62	2.0	0.047
				4.00	(> 5.0)	4.55	7.3	0.070
1.0	0.00	0.02	Adaptive	3.25	Stable	Stable	...	...
				3.50	Stable	Stable	...	...
				3.75	(> 5.0)	4.61	2.1	0.047
				4.00	(> 5.0)	4.47	11.3	0.062
1.0	0.00	0.04	Nonadaptive	3.25	4.82	4.62	0.6	0.033
				3.50	(> 5.0)	4.63	1.1	0.041
				3.75	(> 5.0)	4.59	2.9	0.056
				4.00	(> 5.0)	4.45	26.3	0.126
1.0	0.00	0.01	Nonadaptive	3.25	Stable	Stable	...	...
				3.50	Stable	Stable	...	...
				3.75	Stable	Stable	...	...
				4.00	4.66	(< 4.4)	(?)	(?)

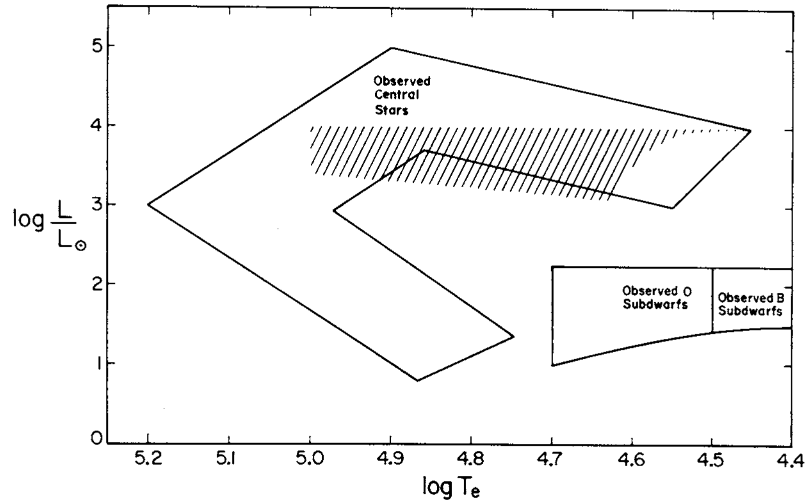

FIG. 1.—Theoretical H-R diagram showing the predicted (shaded) region of pulsational instability in the fundamental radial mode for models of hot subdwarfs with $Z = 0.04$. Pulsational instability probably extends to brighter luminosities and to hotter effective temperatures than are actually plotted. The zones of occupation of observed central stars of planetary nebulae (O'Dell) and of observed O and B subdwarfs (Greenstein and Sargent) are also shown.

III. DISCUSSION

On the H-R diagram of Figure 1 are plotted the characteristic domains occupied by highly evolved stars of low mass that have bright luminosities and hot effective temperatures. These stars are the central stars of planetary nebulae (O'Dell 1968) and the old O and B subdwarfs (Greenstein and Sargent 1974). Their masses probably lie somewhere in the range 0.4–1.2 $M_\odot$.

Our theoretical models predict that only very bright central stars should be pulsationally unstable (in the fundamental radial mode), unless Z in the envelope is substantially larger than 0.04. Possibly, low radial overtones are also unstable, but the effect of convection on the pulsation modes is uncertain. However, the derived *lower boundary* of the pulsational instability strip is believed to be securely determined for each value of Z, because the stellar envelopes for luminosities near this boundary and fainter are mostly in radiative equilibrium below the superficial helium ionization zone. Pulsational instability probably does not occur at any luminosity with the present opacities if $Z < 0.005$.

Unfortunately, little is known observationally, in any definite way, about the range of luminosities and metals abundances applicable to the rapidly varying central stars. But empirical time scales that range from minutes to hours could readily be explained by the theoretical results obtained here. It would therefore be interesting to determine whether the observed variability is confined to the stars with very bright luminosities showing significant CNO abundances.

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